

Outburst activity of symbiotic system AG Dra

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ABSTRACT

AG Dra is a well known bright symbiotic binary with a white dwarf and a pulsating red giant. The long-term photometry monitoring and a new behaviour of the system are presented. The detailed period analysis of photometry as well as spectroscopy was carried out. In the system of AG Dra, two periods of variability are detected. The longer one around 550 days is related to the orbital motion, and the shorter one around 355 days is interpreted as pulsations of the red giant in our older paper. In addition the active stages change distinctively, but the outbursts are repeated with the periods from 359 to 375 days.

Key words: stars: binaries: symbiotic – stars: individual: AG Dra – stars: oscillations

1 INTRODUCTION

AG Dra is a classical symbiotic binary, type S. It is one of the best studied symbiotic systems, thanks to its relatively high brightness (about 9.8 mag in quiescence and about 8.3 mag in the largest outbursts in V), high Galactic latitude ($b = 41^\circ$) favourable for observations and low extinction ($E_{(B-V)} = 0.05$, Mikolajewska et al. (1995)).

The cool component of AG Dra is a relatively early spectral type with the classification in the range from K0 to K4, and of low metallicity, $[\text{Fe}/\text{H}] = -1.3$ (Smith et al. 1996). Mass of the giant was estimated on $1.5 M_\odot$ by Kenyon & Fernandez-Castro (1987). Its luminosity could be higher than that of standard class III (Huang et al. 1994; Mikolajewska et al. 1995). Smith et al. (1996) found the overabundance of elements heavier than Fe (mainly Ba and Sr) and thus classified the giant as a barium star. Such stars are on average more luminous than standard giants of the same spectral class and they could be more capable of invoking symbiotic activity in the binary system due to their higher mass loss rate. The radius of the giant was estimated to be $\sim 35 R_\odot$ by Zamanov et al. (2007) and Garcia (1986) found an orbital separation of $400 R_\odot$. If we estimate the Roche lobe radius on the basis of the mentioned values, we can conclude that the giant probably does not fill its Roche lobe.

The hot component of AG Dra is considered to be a white dwarf sustaining a high luminosity ($\sim 10^3 L_\odot$) and temperature ($\sim 10^5$ K) due to the thermonuclear burning of accreted matter on its surface (Mikolajewska et al. 1995).

The accretion most likely takes place from the stellar wind of the cool giant. Both components are in a circumbinary nebula, partially ionized by the hot component.

AG Dra undergoes characteristic symbiotic activity with alternating quiescent and active stages. Active ones consist of several outbursts repeating at about a one-year interval. The amplitudes of the outbursts decrease toward the longer wavelengths, from ~ 1 mag in V to ~ 3 mag in U . Periodical outbursts and their relation to the orbital motion of the binary system have been a matter of long-term debate. While there is general agreement that the orbital period of AG Dra is about 550 days (Meinunger et al. 1979; Gális et al. 1999; Fekel et al. 2000), there are variations on the shorter time scales (350–380 days) presented by Bastian (1998), Friedjung et al. (1998, 2003) and some others. Understanding the nature and mechanism of this variability is crucial in order to explain the outburst activity of AG Dra and other classical symbiotic stars.

González-Riestra et al. (1999) showed on the basis of the analysis of all *IUE* observations that there are two types of outbursts: the cool and the hot one. During the cool outburst (e.g. 1981 - 83 and 1994 - 96), the hot compact object has a temperature $\approx 90\,000$ K thus lower than that in the quiescent stage. The hot outbursts (e.g. 1985 - 1986) are characterized by temperatures above $\approx 130\,000$ K and considerably lower optical and UV brightness.

Skopal et al. (2009) studied the supersoft X-ray vs. optical/UV flux anticorrelation of AG Dra. They concluded that such behavior is caused by the variable wind from the hot component of the system. Shore et al. (2010) found that variations in the Raman features ratio, during the outburst, are consistent with the disappearance of the O VI far UV

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resonance wind lines from the white dwarf. The observations support the suggestion that the soft X-ray and UV variations are due to the expansion of the envelope and decreasing the effective temperature of the gainer star. The outburst activity (2006 - 2008) of AG Dra was studied by Munari et al. (2009) using of the photometric and spectroscopic observational material. The first outburst of this activity stage was one of the cool type and was followed by the fainter maximum of the hot type after 375 days. Contini & Angeloni (2011) mentioned that the collision of the wind from the white dwarf with the dusty shells, ejected from the red giant, leads to the fluctuations in U band during the major outburst. The long-term spectroscopic study of AG Dra was presented by Shore et al. (2010). They discussed the effects of the environment and orbital modulation in this system. Recently Leedjäv & Burmeister (2012) demonstrated spectroscopic behaviour of AG Dra before, during and after the last outburst.

Recently Formigini & Leibowitz (2012) accomplished complex period analysis of the historical optical light curve of AG Dra, covering the last 120 years. They found that the period of the outbursts was 373.5 days and a cyclical behaviour with a quasi-period of 5300 days. The last one is the time interval between the start of the active stages induced by the solar-like cycles of magnetic activity. The combined effect of the 5300 and 373.5 days cycles augments the postulated cool giant pulsations of the red giant with the period of 350 days (Formigini & Leibowitz 2012). However, the proposed rotational period of the giant of 1160 days in their model, and in particular, its retrograde rotation seems to be somewhat artificial and not well justified physically.

In the present paper, we re-analyze the $UBVR$ light curves of AG Dra and also apply time series analysis to the spectroscopic data. We use all the available photometry, starting from the compilation of photographic observations by Robinson (1969) and proceeding with a large amount of photoelectric observations (see hereafter). Variability of the emission lines provides an additional information of the physical state of the AG Dra system.

2 PHOTOMETRIC AND SPECTROSCOPIC DATA

The new photoelectric and CCD observational material¹ was obtained at observatories at Skalnaté Pleso (SP), Stará Lesná (SL-G1 and SL-G2) and Valašské Meziříčí (VM). At the observatories SP and SL-G2 identical Cassegrain telescopes with a diameter of 0.6 m were utilised. One-channel photoelectric photometers with digital converters were used, as well as standard $UBVR$ Johnson's filters. CCD photometry was performed at SL-G1 using the 0.5-m telescope. The SBIG ST10 MXE CCD camera with a chip of 2184×1472 pixels and the $UBV(RI)_C$ Johnson-Cousins filter set were mounted at the Newtonian focus.

Schmidt-Cassegrain (280/1765 mm) equipped with CCD ST-7 and set of VR filters was used at VM observatory. From JD 2450 563 to JD 2451 179 photographic films

Observatory	N_{nights}	Period	Period [MJD]
SP + SL-G2		18.5.1999 – 16.3.2012	51 317 – 56 003
SL-G1		31.7.1994 – 27.9.2009	49 565 – 55 102
VM		24.4.1997 – 24.4.2005	50 563 – 53 485

Table 1. List of observational nights on particular observatories: SP - Skalnaté Pleso, SL-G1 - Stará Lesná, pavilion G1, SL-G2 - Stará Lesná, pavilion G2 and VM - Valašské Meziříčí.

as a detector were used. The number of observational nights, observational intervals in the date as well as in Julian days for particular observatories are listed in Table 1. In addition, we used the same data that had already been analyzed and discussed in our previous paper (Gális et al. 1999) and published photoelectric UBV photometry by Belyakina (1965, 1969), Skopal et al. (2002), Leedjäv et al. (2004), Skopal et al. (2004), Munari et al. (2009), Skopal et al. (2012) as well as photographic measurements by Robinson (1969) and Luthardt (1983).

To support the model of cool giant pulsations we obtained the photometric observations in instrumental ΔR_i magnitude. These magnitudes were not transformed to the international system due to the lack of the comparison star R magnitudes. These observations were secured in the period from JD 2 449 557 (July 23, 1994) to JD 2 455 102 (September 27, 2009) at the SP and SL-G1 observatories and part of them was published by Skopal & Chochol (1994), Skopal et al. (1995), Hric et al. (1996), Skopal (1998), Skopal et al. (2002, 2004, 2012).

Intermediate dispersion spectroscopy of AG Dra was carried out at the Tartu Observatory in Estonia. The data used in this paper covered the interval from JD 2 450 702 (September 11, 1997) to JD 2 455 651 (March 31, 2011). All together 211 spectra of AG Dra were used for the period analysis. The spectroscopic material was taken by the 1.5 m telescope equipped with the Cassegrain grating spectrograph. The equipment and method of observations were described in Leedjäv et al. (2004) and Leedjäv & Burmeister (2012). The majority of the spectra were recorded in two spectral regions which we call red and blue. Red spectra were taken with a dispersion of 0.47 \AA/pix at H_α and they include emission lines of H_α , He I 6678 \AA and the Raman scattered O VI line at 6825 \AA . The blue spectra included at least, emission lines of H_β , He II 4686 \AA and He I 4713 \AA . The dispersion of the blue spectra was about 0.57 \AA/pix at H_β . The spectra were reduced using the software package MIDAS provided by *ESO*. The wavelength-calibrated spectra were normalized to the continuum and positions, peak intensities and equivalent widths (EW) of the emission lines were measured².

3 MORPHOLOGY OF THE LIGHT CURVES AND PERIOD ANALYSIS

In this section, there are described the results of re-analysis of the historical light curve from the photographic data up to 1966. We have also presented the results of the analysis

¹ The photometric data are available upon request from the authors.

² The spectroscopic data are available upon request from the authors.

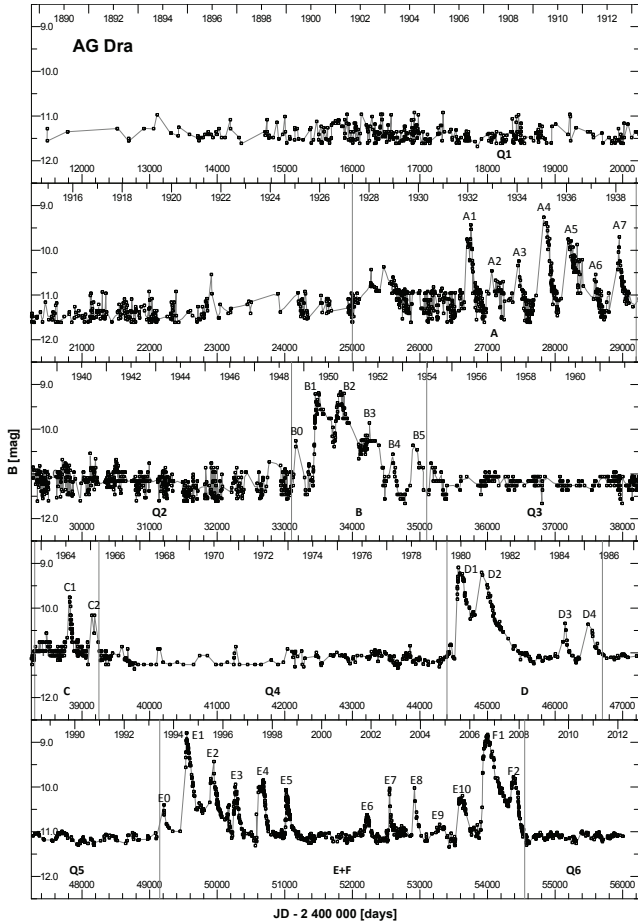


Figure 1. The historical LC of AG Dra from period 1889 - 2012 constructed on the basis of photographic and *B* photoelectric observations. The used data sources are quoted in the text. The LC is divided to active (A - F) and quiescence stages (Q1 - Q6) by vertical lines. The thin curve shows a spline fit to the data points.

of UBV photometry from 1974 to the present day. The results of principal component analysis of UVB photometry are also discussed.

The period analysis of the observational data was performed using an advanced implementation of the Date Compensated Discrete Fourier Transform. We used a Fisher Randomization Test (Monte Carlo Permutation Procedure) to calculate two complementary False Alarm Probabilities (FAP) for determining the significance of a given period P : FAP 1 represents the proportion of permutations containing a period with a peak/valley higher (respectively lower) than the peak/valley of P at any frequency. It is the probability that there is no period in the period window (power spectrum) with value P . FAP 2 represents the proportion of permutations containing a period with a peak/valley higher (respectively lower) than the peak/valley of P at exactly the frequency of P . It is the probability that the observation data contain a period that is different from P . This test executes the selected period analysis calculation repeatedly (at least 100 times), each time shuffling the magnitude values of the observations into the form of a new randomized observation set, but keeping the observation times fixed (Press et al. 1992). FAPs with value below 0.01 (1%) mostly indi-

Table 2. The results of the period analysis of historical light curve of AG Dra constructed on the basis of photographic and *B* photoelectric observations. T_{start} marks the beginning and T_{end} the end of the given stage. During stages Q1, Q2 and Q3 was the system quiescent whereas stages A, B and C are active.

Phase	T_{start} [MJD]	T_{end} [MJD]	Significant periods [days]
Q1	11 500	25 000	551.0 ± 3.5 ; 348.8 ± 2.1
A	25 500	29 200	371.3 ± 4.6 ; 548.0 ± 8.1
Q2	29 200	33 100	399.6 ± 5.6
B	33 100	35 100	352.7 ± 5.9
Q3	35 100	38 300	438.0 ± 10.7 ; 534.0 ± 23.9
C	38 300	39 250	380.2 ± 10.2
Q4	39 250	44 400	550.0 ± 10.3 ; 350.9 ± 4.8

cate the significant periods. FAPs above 0.20 (20%) mostly relates to an artifacts in data, instead of a true period.

In addition, we created a spectral window to confirm that the periods found in the previous steps are not artifacts of the observing rate. We performed the detail period analysis for some complicated cases (e.g. during active stages), in which the response of examined period P was removed from the data and the power spectra of such residuals were studied with a focus on persistent presence of aliases and harmonics of this period. The minimum period error (or period uncertainty) of the period P was determined by calculating a 1-sigma confidence interval on P , using a method described by Schwarzenberg-Czerny (1991).

3.1 The light curve between the years 1890 and 1966

The first historical photometric observations were dated to the end of 19th century (Fig. 1). During the period (1890 - 1996) the AG Dra system underwent 3 phases of activity: the first one between the years 1932 and 1939, the second one between 1949 and 1955 and the third one between 1963 and 1966. In total, we recognised 15 outbursts in this period: seven during the first active phase, six during the second one and two outbursts during the last one.

We present the results of the re-analysis of this data with contemporary method described in Section 3. We divided the light curve into quiescent and active stages (marked by vertical lines in Fig. 1) and carried out a period analysis independently for each stage. We present the results of this analysis for the given stages in Table 2 as well as in Fig. 2. We can conclude that the historical light curve shows both known periods: ≈ 550 days (orbital period) and ≈ 350 days (the period of postulated pulsation of the red giant, Gális et al. (1999)). Besides these periods the analysis gave us the period 370 - 380 days which is present in the active stages A and C. This period is related to the recurrence of the individual outbursts occurred in these active stages. The periods around 400 days (Q2) and 440 days (Q3) are probably not real and are caused by the low amplitude of light variations in comparison with the scatter of these photographic data.

Between the years 1889 and 1927 (stage Q1) AG Dra was in quiescence with a mean photographic brightness 11.02 mag. Small variations of the LC revealed the presence of both known periods. After this, at least 38 years of quies-

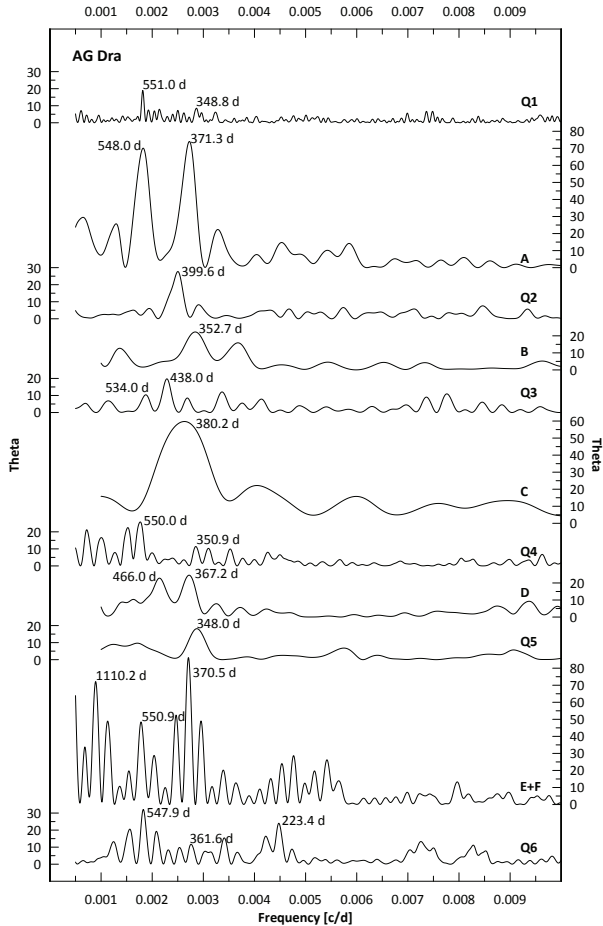


Figure 2. Power spectra of AG Dra taken from historical photographic as well as photoelectric and CCD data in *B* filter for particular stages of quiescence (Q1 - Q6) and activity (A - F). Significant periods are marked with their values.

cence, the system went into an active stage (assigned by A in Fig. 1). Until the year 1938 we can recognize seven major outbursts occurring approximately every 300 - 400 days. The individual outbursts have a rather steep rise to the maximum and a fast decline. The outburst in the year 1932 (A1) had two maxima with a second (more prominent) maximum following the first one after ≈ 50 days. The system reached the maximal brightness of 8.9 mag during the fourth outburst (A4). For the next almost 11 years a quiescent stage followed with only small semi-regular variations. The period analysis gave us a period with a value ≈ 400 days, which is more probably related to the data distribution in this part of the LC (see stage Q2 in Fig. 1) as the real brightness variability of AG Dra system. This distribution might have drowned the expected orbital or probable pulsation period. An epoch of intense activity was observed between the years 1949 and 1955 (stage B). The overall morphology of the LC during this active stage is rather different from that of stage A. The peaks have an analogously steep rise to the maximum with the highest achieved brightness 8.8 mag. The decrease is considerably slower and unlike stage A, the system spends most of this period above 10.5 mag. The outbursts follow one after another ≈ 350 days. The second and third

outbursts (B2 and B3) might have again secondary maxima approximately 50 days after the primary ones.

Stage Q3 (1955 - 1963) is characterised by the semi-regular featureless brightness variations with period ≈ 440 days. This behaviour probably influenced the value of the orbital period (534 days) obtained by our analysis. The system became active after the year 1963, which resulted in the shortest (1963 - 1966) and the least active (only 2 - 3 outbursts) stage during whole observed LC of AG Dra. The period analysis of this active stage C revealed the presence of 380 days period.

3.2 The light curve after 1966

For complete coverage of the 124 year history of AG Dra we are missing an 8 years part on the LC between JD 2439355 (August 17, 1966) and JD 2442109 (March 2, 1974). In the archive of the Sonnenberg Observatory we have found two papers (Splittgerber 1974; Luthardt 1983) where the LC behaviour during this period is described, but the data was not available. We extracted the photometric data from the LC depicted in Fig. 2 in the paper by Luthardt (1983) to cover the missing part of the historical LC. It was obvious from the completed LC (Fig. 1) that after the outburst C the system fell into the long-term quiescent stage (assigned as Q4). The activity of the system was very low during this period and the average photographic brightness was 10.9 mag. The period analysis of this part of the LC shows unambiguously the presence of 550 days orbital as well as 350 days postulated pulsation period.

The quiescent stage Q4 is partly covered by photoelectric observations, too. The first photoelectric UVB photometry of AG Dra was obtained by Belyakina from 1962 to 1967 (Belyakina 1965, 1969). Since 1974 the system of AG Dra has been observed systematically mainly photoelectrically in UVB. The merit of good coverage of the LC has been our campaign (Hric & Skopal 1989), too. The benefits of this data were the improvement of the orbital period (≈ 550 days) and the discovery of the shorter period (≈ 350 days), which was interpreted as the pulsation of the cool component (Gális et al. 1999). The photoelectric LCs of AG Dra are depicted in particular filters in Fig. 3. It is obvious from the LCs in *U*, *B* and *V* bands, that the amplitudes of variations decrease towards longer wavelengths. During the activity of the system the LCs are in strong correlation in all bands. The variations in quiescence are similar in *B* and *V*, but differ in *U* bands.

In 1980 the system entered the active stage D, where outbursts were characterized by fast increase and slower decrease as in stage B. The individual outbursts are clearly recognised in Fig. 3. It is worth noting that the active stage D was interrupted by the interval (1983 - 1985) when the system manifested the behaviour typical for quiescent stages. AG Dra was in quiescent stage (Q5) for the next 7 years. In 1993 new activity (E) started with the small outburst followed by the next 5 prominent outbursts consecutively in $\approx 350 - 390$ days intervals. Activity of the system was again interrupted by a short quiescent-like interval in 1999 - 2001 (similar to the behaviour happened during the active stage D) and continued by the next 5 outbursts which finished at the beginning of 2006. Such long-term activity has never been observed during more than one century of photometric

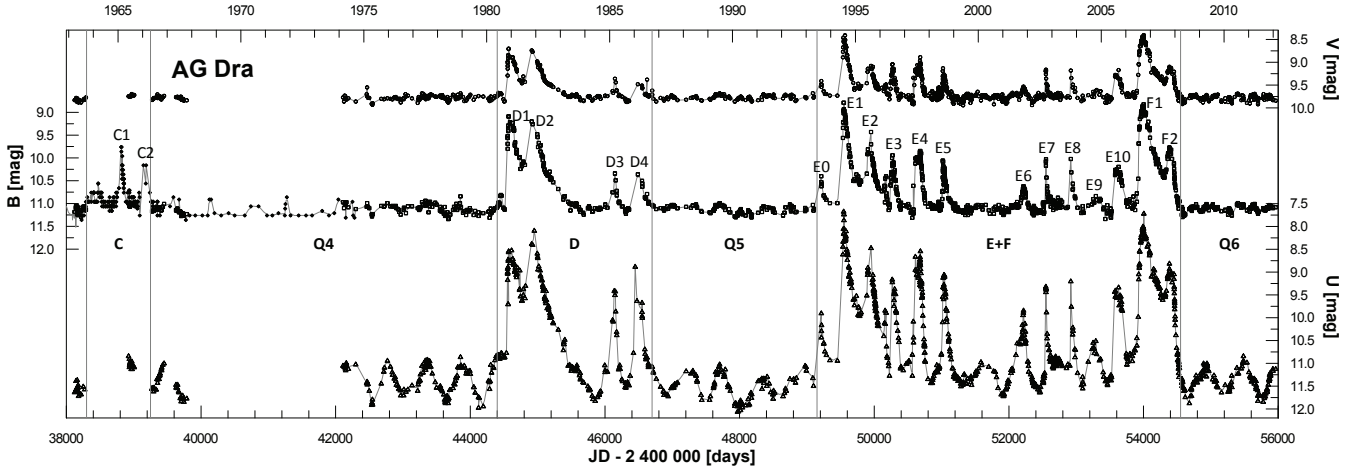


Figure 3. UBVC LCs from the period 1963 - 2012 with marked active stages (C, D, E and F) and quiescent ones (Q4, Q5 and Q6). Particular outburst are assigned as C1 - C2, D1 - D5, E0 - E10 and F1, F2. The thin curves show a spline fits to the data points.

Table 3. The results of period analysis of particular stages between 1963 - 2012. LCs for each filter were analyzed separately. T_{start} is beginning and T_{end} the end of the given stage. The periods are in order according to their significance.

Phase	T_{start} [MJD]	T_{end} [MJD]	U band	Significant periods [days] B band	V band
Q4	39 250	44 400	551.0 ± 2.4	550.0 ± 10.3 ; 350.9 ± 4.8	349.6 ± 13.9 ; 550.0 ± 49.7
D	44 400	46 700	371.9 ± 5.5	367.2 ± 8.1 ; 466.0 ± 15.2	372.5 ± 6.1
Q5	46 700	49 150	553.6 ± 4.0	348.0 ± 6.7	350.1 ± 7.3
E + F	49 150	54 550	371.2 ± 1.8	370.5 ± 1.9 ; $1\,110.2 \pm 18.5^a$; 550.9 ± 9.8	370.5 ± 1.8
Q6	54 550	continue	549.3 ± 2.7	547.9 ± 6.4 ; 223.4 ± 5.3^b ; 361.6 ± 5.3	357.3 ± 19.8

Notes:

a - The period of $1\,110.2 \pm 18.5$ days is probably only double of 550.9 ± 9.8 days one.

b - The period of 223.4 ± 5.3 days is 1-year alias of 547.9 ± 6.4 days one.

The global morphology of active stages D and E+F is possible very well describe by sinusoidal variations with periods around 1110 days (or double 2220 days) and 2500 days (or double 5000 days).

history of AG Dra. This activity was immediately (without quiescence phase) followed by the large outburst (F1) in 2006 when the brightness in U reached 8 mag. This new phase of activity (F) had two (up to JD 2 455 000) outbursts followed by a fast drop to the deep brightness minimum (11.8 mag in U band). Since 2008 the symbiotic system AG Dra has been in quiescent stage (Q6).

From the light curve in Fig. 3, we can distinguish two kinds of outbursts. There are main double-peaked outbursts (B1 and B2, D1 and D2, E1 and E2, F1 and F2) with very rapid increase of brightness, small drop of magnitude between peaks and slow decrease to the quiescence level. The identification of double-peaked outburst is ambiguous during the active stage A and such a feature is totally missing in the weak active stage C. This type of outbursts defines the beginning of each new cycle of activity of the AG Dra with time interval 12 - 16 years. Moreover, there are outbursts with the sharper shape and lower amplitude which are observed after main outburst and sometimes during the whole cycle of activity (B3 - B5, C1 - C2, D3 - D4, E3 - E10).

Our statistical analysis of the photoelectric and CCD observations shows that the light curves in U , B and V filters were very well correlated (correlation coefficients ≈ 0.9) during the active stages (D, E and F in Fig. 3). During the quiescent stages (Q4 - Q6 in Fig. 3), the correlation coef-

ficient of the LCs in band U and B as well as one of LCs in band U and V are less than 0.5. On the other hand the variations in B and V bands are correlated quite well during the quiescence. This result showed that the brightness variations during quiescent stages of AG Dra in the various bands were caused by different physical mechanisms.

We performed the period analysis of LCs in individual bands (U , B and V) with the same methods used for period 1890 - 1966. The results of this analysis are presented in Table 3. The power spectra of AG Dra in U , B and V filters for active stages as well as for quiescence are depicted in Fig. 4. As we have shown by our period analysis of the quiescent stages, the light curve in U band is clearly dominated by variations with the orbital period ≈ 550 days. In the bands B and V , we found the shorter period (≈ 350 days); although, its value in each quiescent stage changed slightly. The period analysis of the active stages revealed many significant periods. Our detailed analysis showed that most of the periods were more likely related to the complex morphology of the light curves during the active stages than the real variability present in this symbiotic system.

The significant period with a value of around 370 days is related to the distribution of individual outbursts, which dominate the light curve in the active stages. It should be noted, however, that the value of this period varies with wavelength and is different for the individual active stages.

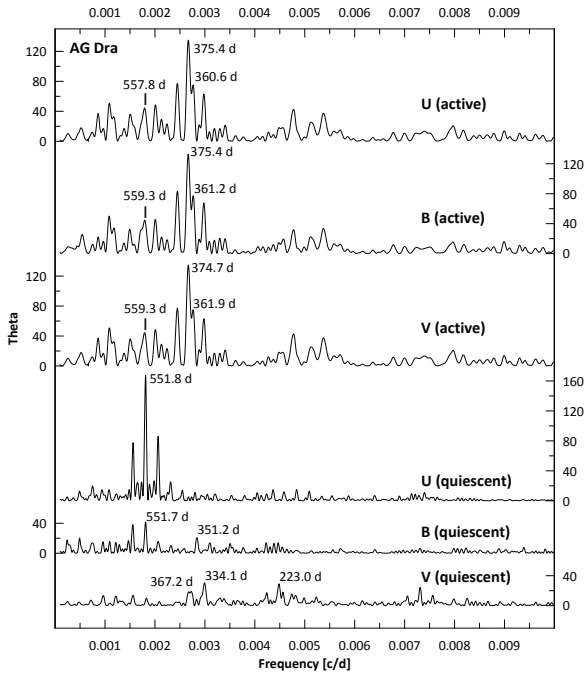


Figure 4. Power spectra of AG Dra taken from photoelectric and CCD data in U , B and V filters for active (D, E+F) and quiescent (Q4 - Q6) stages. Power spectra for active stages in U , B and V filters were obtained after removing of long-term periods around 1500 and 5400 days, which are related to the global morphology of these active stages.

Statistical analysis of the outburst distribution shows that the median of the time interval between the individual outbursts is 365 days, while the time intervals vary from 300 to 400 days without apparent long-term trend.

We can conclude, that the results of period analysis of UB V LCs strongly confirm both known periods. The dominance of the orbital period in U filter is in agreement with the model by Gális et al. (1999).

Stronger influence of the second period in longer wavelength suggests its relation with the behaviour of the red giant and probably is caused by its pulsations as it was proposed by us in the paper mentioned above.

3.3 Differential R_i photometry of AG Dra during 1994 - 2009

As we have shown in the previous section, two periods are present in the LCs of AG Dra. For the 350 day period Gális et al. (1999) proposed the interpretation as pulsations of the cool giant. To support this model we carried out the period analysis of photometric observations in instrumental ΔR_i magnitude.

We had at our disposal, 226 nights of observations covering part of the active phase (E in Fig. 3). All observations are depicted in Fig. 5. Pronounced outbursts as well as variations during quiescence are modulated with the period $P_R = (371.0 \pm 2.2)$ days. The presence of this period at longer wavelength during quiescence of AG Dra probably suggests its relation to the cool component in this system.

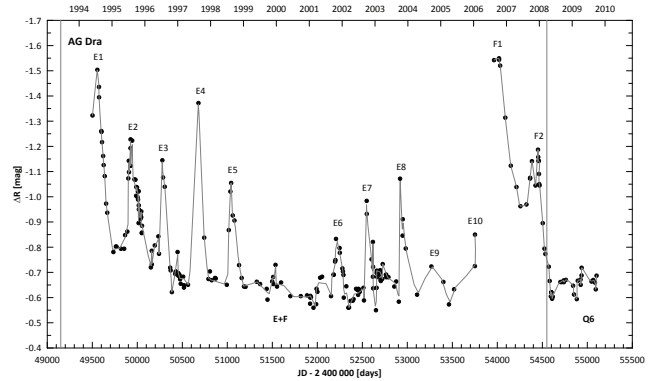


Figure 5. Light curve of AG Dra in instrumental ΔR_i mag. The thin line shows a spline fit to the data points.

The red giant pulsations proposed by Gális et al. (1999) are the possible source of modulations with this period.

3.4 Results of principal components analysis of UB V photometry

We accomplished the principal component analysis (PCA) of UB V photometry from the period 1974 - 2006. We analysed the whole light curve and then particular stages (Q4, D, Q5 and E) separately. PCA is a type of linear orthogonal transformation (also known as discrete Karhunen-Loève transform or Hotelling transform) to convert a set of observations of possibly correlated variables into a set of values of linearly uncorrelated variables, called principal components. This transformation is defined in such a way that the first principal component (PC1) has the largest possible variance, and each succeeding component in turn has the highest variance possible under the constraint that this component is orthogonal to the preceding ones.

For this analysis, only the observations with magnitudes in all three filters were used. There were composed the input values of three vectors $U \equiv (U_{t1}, U_{t2}, \dots, U_{tN})$, $B \equiv (B_{t1}, B_{t2}, \dots, B_{tN})$ and $V \equiv (V_{t1}, V_{t2}, \dots, V_{tN})$, where U_{ti} , B_{ti} and V_{ti} were magnitudes in particular filters in time t_i and N is number of observations. The output of the method is ternary of vectors PC1, PC2 and PC3, which represents principal components of input observations. They have N dimensions as the input vectors and therefore it is possible to assign time t_i and create the light curves of principal components (see Fig. 6). The diagrams in this figure represent the light curves of principal components computed for the period 1974 - 2006. If we compare the components with the original light curves, we can see that the first component PC1 includes the most of the significant variations in original data. The second component PC2 contains the variation related to the orbital motion. The last component PC3 does not contain significant information about the binary system, only the noise caused by the errors of the data.

The informational content in the particular components is possible to quantify by variation analysis. The amplitudes of variations in U , B and V bands decrease towards the longer wavelengths. We scaled the original U , B and V light curves to unit variations to secure the same weights for the LCs inputting into the analysis. It is evident from the Table

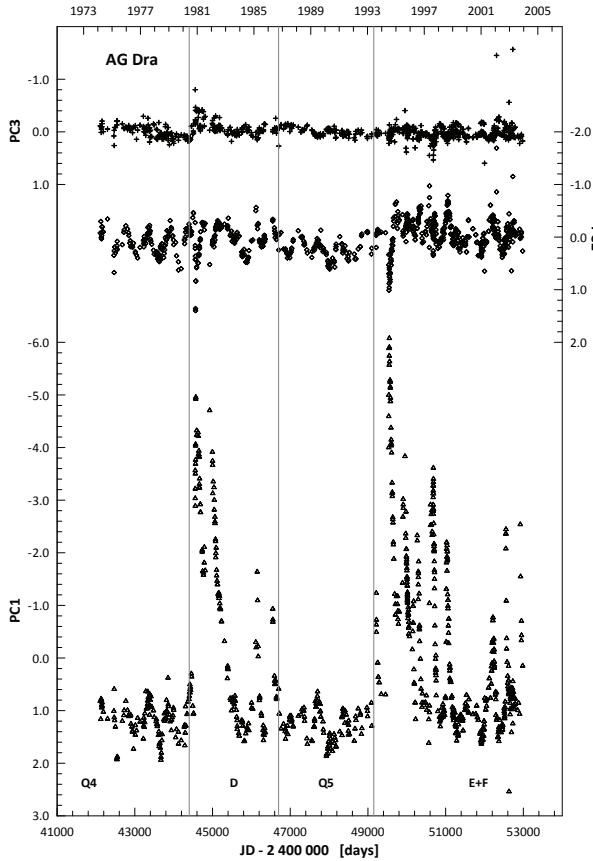


Figure 6. Principal components PC1, PC2 and PC3 for AG Dra UVB light curves.

4, that output components are not equivalent. The variation of PC1 composes as far as 96.3 % of the variation of input data and so represents 96.3 % of entire information content. That is caused by the mechanism of PCA which selects the principal component PC1 so that its correlation with the input signal is the highest. The whole variation of principal components is equal to the whole variation of input data. It means that the principal components contain whole information about input light curves.

In the next step the light curves were divided into the particular stages (Q4, D, Q5, and E) and the variation analysis was accomplished for each stage separately. This analysis gave similar results as in the case of the whole LCs.

Apart from variation analysis of particular components, it is interesting to study their correlations as well as the correlations to the original light curves. We analysed correlations among all combinations of light curves (U , B , V) and principal components (PC1, PC2, PC3). Very interesting are the correlations of the light curves in particular filters. During the activity these correlation coefficients are very high (≥ 0.97). The behaviour of U , B and V light curves are equivalent, because outbursts are dominating features in all bands. In this manner, we detected high correlation with PC1, too. The behaviour of quiescent stages are different. The light curves in U and B bands have a correlation coefficient ≈ 0.7 , but in U and V bands have a correlation coefficient only ≤ 0.5 , because the orbital period is dominat-

Table 4. Variation analysis of principal components of whole period (1974 - 2006)

Component	Variation	Cumulative sum
PC1	2.889	2.889
PC2	0.089	2.979
PC3	0.021	3.000
The original light curves:		3.000

Table 5. The results of period analysis of principal component (PC1) for particular stages in 1974 - 2006.

ID	Significant periods [days]
Q4	563.9 ± 11.2 ; 343.0 ± 5.6
D	484.5 ± 7.2 ; 367.9 ± 4.1
Q5	575.6 ± 11.5 ; 348.1 ± 3.8
E	367.9 ± 1.1 ; 526.1 ± 3.6

ing in U band while the probable pulsation period is more significant in V band.

The brightness variations related to the orbital motion as well as the probable red giant pulsation should be present in all three bands, but with different amplitudes. The method of PCA transforms the variations into the first principal component. Moreover, the advantage of PC1 period analysis in comparison with analysis in particular colours is such, that the first principal components contain the most of the informations, the noise is suppressed (is isolated in the last component) and the detected periods have higher statistical significance. Therefore we accomplished the period analysis of PC1. The result of this analysis for particular stages are listed in Table 5. The principal component PC1 contains two significant periods around 550 and 350 days, even the individual values of detected periods vary from 343 to 368 days and from 526 to 576 days for postulated pulsation and orbital periods, respectively. The presence of 368 days period is possible to explain by the time distribution of individual outbursts during active stages. The large scatter in the values of orbital period (larger than the typical error of period determination) as well as the presence of 485 days period is not clear.

Fig. 6 suggests that the principal component PC2 contains only the orbital variations. The period analysis of PC2 in whole time interval (1974 - 2006) revealed the orbital period $P_{PC2} = (555.9 \pm 1.2)$ days. This orbital period is also dominating in the period analysis of particular stages (Q4, D, Q5 and E) except D, where the detected period is ≈ 480 days. The period analysis of PC2 confirmed also the presence of the shorter period $\approx 340 - 370$ days in all particular stages, but with lower significance than in PC1. In the light curve of PC2 (see Fig. 6) faint suggestions of outbursts in stages D and E are also visible. The period analysis of PC3 did not give the presence of any significant period.

The activity of the system is manifested in differential R_i photometry, too. From all observational nights, the data with magnitudes in all four filters were selected. For the 98 observations, the variation analysis as well as the period analysis of principal components were performed. The variation analysis showed that during the active stages the light

curve in ΔR_i band correlated well with LCs in all another bands. For correlation coefficients, the following values were obtained: $C_{RU} = 0.95$, $C_{RB} = 0.97$, $C_{RV} = 0.97$. It means that the outbursts are dominated in the red light curves, too. The period analysis of the principal component PC1 disclosed the significant presence of the "postulated" pulsation period $P_{pul} = (352.4 \pm 6.3)$ days. The next significant period $P_{orb} = (544.2 \pm 17.4)$ days is close to the value determined for the orbital period. In the light curves PC2 and PC3, only unreal periods around 700 days were found. The last component PC4 did not reveal any significant periods.

4 PERIOD ANALYSIS OF SPECTROSCOPIC DATA

For the period analysis of the radial velocities, we used the method of Fourier harmonic analysis (Andronov 1994), which fits the first harmonic term of a trigonometric polynomial approximation and Variable Stars Calculator (Breus 2003), which utilised Lafler-Kinman-Kholopov method. For verification of the results, the method of Fourier analysis (Ghedini 1982) was used.

4.1 Period analysis of absorption lines

In our previous papers (Gális et al. 1999; Friedjung et al. 2003) we performed detailed period analysis of radial velocities based on absorption lines measurements. We would like to note that these measurements have very high accuracy with typical errors (0.4 - 0.8 km/s). The data (135 radial velocities) cover the time interval JD 2 446 578.5 - 2 451 676.9 (5098 days). We reanalysed all these data to confirm the presence of periods longer than 1000 days. We detected only two significant periods 550.4 ± 1.4 and 355.0 ± 1.6 days related to the orbital motion and cool component pulsations, respectively. The power spectra taken from combined radial velocities based on absorption line measurements are depicted in Fig. 7. We can confirm that the data did not contain variability with longer periods. Moreover, the statistical analysis suggests that data with those errors did not contain other signal except orbital motion and postulated pulsation ones.

4.2 Period analysis of emission lines

We have obtained equivalent widths (EW) and absolute fluxes of spectral emission lines H_α , H_β , He I 6678 Å, He II 4686 Å and Raman scattered O VI 6825 Å as well as radial velocities of these lines (except the O VI 6825 Å line). The variability of EW of some spectral lines of AG Dra is well known already for many years, and many authors have made a great effort to assign this variability to present physical mechanisms in the system (Kaler 1987). Up to now, this variability has not been explained without uncertainties. The variation of EW is related to the increase or decrease of the amount of observed emitted/absorbed particles. This variability would be related to the orbital motion in dependence of orientation of the system towards the line of sight in a given moment (i.e. orbital phase). For more details see Leedjäv et al. (2004).

The results of the period analysis of this data can be

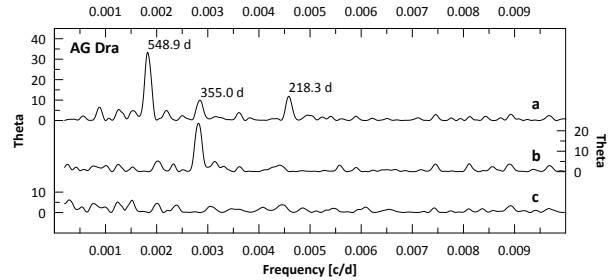


Figure 7. Power spectra of AG Dra taken from combined radial velocities based on absorption line measurements: original data (a), orbital response removed data (b) as well as orbital and probable pulsation response removed data (c).

summarized as follows: The most significant periods detected in radial velocities, fluxes and EWs for all emission lines are close to the orbital period (511 - 568 days) and to the time interval between individual outbursts (366 - 383 days). The period related to the pulsation of the red giant (350 - 357 days) was marginally detected. The period analysis did not show the presence of the longer significant periods around 1160 days like as the analysis of radial velocities based on the absorption lines measurements (see previous section). There are only a few detections of an insignificant period around 1100 days what is the double of the orbital period. The curves of EW for particular spectral lines are depicted in Fig. 8.

5 DISCUSSION AND CONCLUSIONS

The main goal of this paper was the complex and detailed period analysis of photometric and spectroscopic data of AG Dra. The photometry covers the time interval of 124 years, while the last 39 years of photometric observations are based on systematic photoelectric and CCD monitoring. Spectroscopic data were obtained from absorption and emission lines measurements. The results of period analysis of all this data are two real periods present in this symbiotic system: 550 and 350 days related to the orbital motion and postulated pulsation of the cool component, respectively. The orbital period is mainly manifested during the quiescent stages at the shorter wavelength (*U* band), the pulsation period is present during the quiescent as well as active stages at longer wavelengths (*B* and *V* bands). The period analysis of active stages confirmed the presence of around 365 days period what is median of the time intervals between outbursts. It is worth to note that these time intervals vary from 300 to 400 days without apparent long-term trend. The period analysis of the active stages also revealed longer periods (e. g. 1330, 1580, 2350, 5500 days). Our detailed analysis shows that most of these periods are more likely related to the complex morphology of the light curves during the active stages than to the real variability present in this symbiotic system.

Recently, the properties of the light curve of AG Dra covering a period of 120 years were studied by Formigginì & Leibowitz (2012). Their research was mainly based on photographic observations (Robinson 1969) and visual estimates from the AAVSO database. It is worth noting that analysis

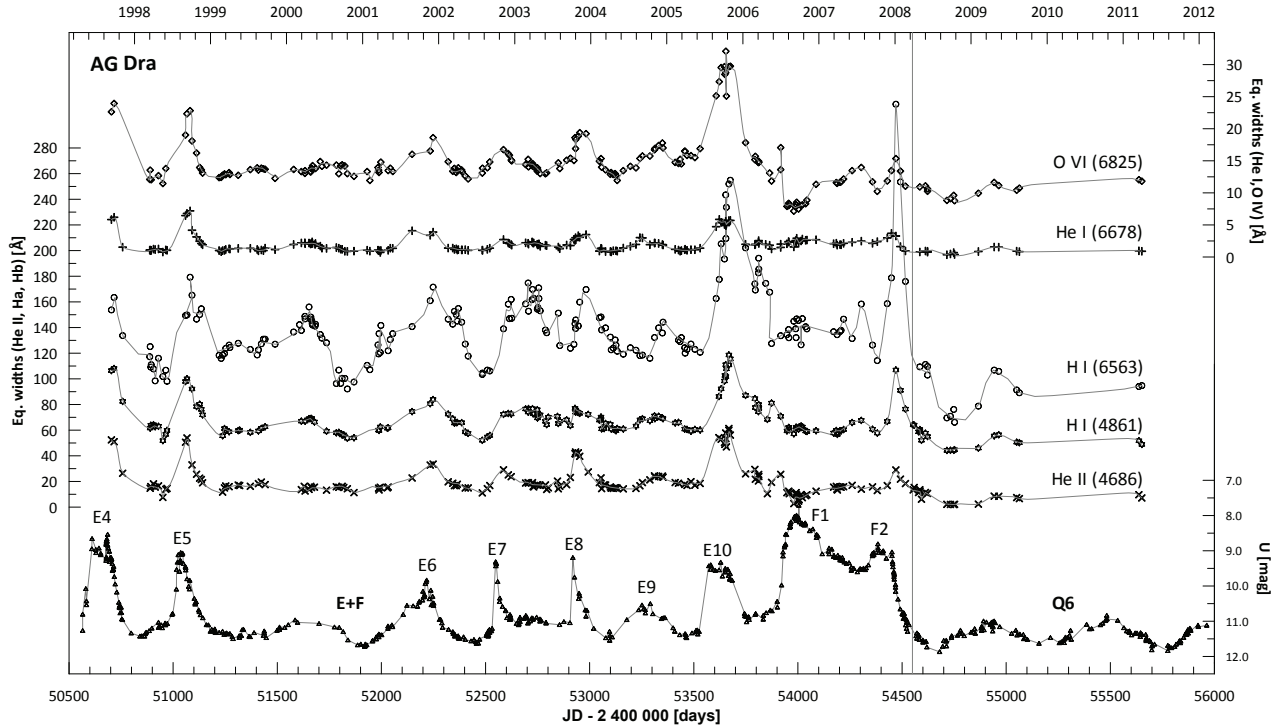


Figure 8. The curves of EW for particular spectral lines. The scales on the left and right axis are valid for EWs of He I (6678 Å) and He II (4686 Å), respectively. The thin line shows a spline fit to the data points.

of such data could give unreal periods (e. g. 400, 440 days periods during Q2 and Q3 stages in our analysis). As complementary observations, Formigini & Leibowitz (2012) used brightness measurements of AG Dra in the filter U from literature. In our opinion, their proposed model is unrealistic and non-physical in some aspects. The result of the LC period analysis of these authors is the detection of the period 373.5 days, that is a mean time interval between the individual outbursts in the active stages. Authors interpreted this period as the synodic rotational period of the cool giant with respect to the white dwarf (for a given point on the giant surface is a white dwarf in the upper culmination every 373.5 days). To secure such synodic rotational period in the binary with the orbital period around 550 days, the giant should rotate retrogradely with a period of 1160 days. The detection of this period is also reported by these authors. We could not confirm the presence of this period in photometric as well as in spectroscopic data. Moreover, such value of the rotational period of the giant is not typical in symbiotic systems (e. g. Table 2, in Formigini & Leibowitz (2012)) and explanation of the retrograde rotation of a component in such an open system from the evolutionary point of view is unclear.

Formigini & Leibowitz (2012) suggest that the cool giant of AG Dra has a very strong magnetic field whose axis is substantially (around 90 degrees) inclined relative to the rotational axis. Moreover, they suggest that the outbursts of AG Dra are the result of intensive outflow of matter from the giant towards the white dwarf. When a region of the magnetic poles of the giant gets to the tidal bulge (strong tidal deformation of the shape of a giant in the direction toward the white dwarf), the balance is disrupted and hydrogen rich

matter is thrown into the Roche lobe of the white dwarf. This will release the large amounts of gravitational energy which becomes apparent as outburst observed in the optical. Since the amount of released matter depends on the intensity of the magnetic field, as well as hydro and thermo-dynamic properties of matter in the tidal bulge at a given time, each outburst can vary greatly. According to the opinion of specialists studying the stellar magnetic activity across the HR diagram, such very strong magnetic fields of cool giant are not known (Korhonen 2013). We do not understand the process of balance breaking by a tidal bulge, in view of the fact that the whole surface of the tidally deformed giant in a binary lies on the same equipotential surface. The authors explain the alternating active and quiescent stages of AG Dra by the mechanism similar to the solar dynamo (responsible for the solar cycle activity), which takes place in the outer layers of the extensive giant atmosphere. Our analysis of all 124 years brightness history has shown that active stages have recurrence 12 - 16 years which is in good agreement with the idea about solar-like activity.

The period analysis of photoelectric and CCD observations obtained during the active stages D and E + F supported the results of our statistical analysis of the data: the light curve in the U , B and V bands are strongly cross-correlated during the activity of AG Dra. The obtained periods in individual bands have the same values within their errors. Global morphology of the active stages is well described by two longer periods (about 1500 and 5400 days). The obtained power spectra contained also a period of about 1 100 days, but the significance of the period decreased considerably after removal of these two longer periods from the light curves of AG Dra (Fig. 4). From this fact we suggested

that the 1100 days period more likely describes only the morphology of the active stages of AG Dra than a real variability presented in this system. The obtained power spectra after removal of the longer periods (about 1500 and 5400 days) showed the presence of a significant period around 375 days (Fig. 4), which is related to the outburst time distribution. As can be seen, the maximum of significance of this period has two peaks (second peak around 360 days), suggesting a possible long-term change of its value. This assumption was confirmed by detailed period analysis of individual parts of the active stage E + F. While at the beginning of E+F stage the power spectrum contains only a period of about 370 days; at the end of this active stage, the power spectrum contains only a period of 360 days. The detection of the period of about 559 days (close to the value of the orbital one), which was significant during the stages of activity in *B* and *V* bands is also interesting.

The situation was different during the quiescent stages (Q4 - Q6) and the period analysis confirmed that the light curve in the *U*, *B* and *V* bands did not cross-correlate. The period analysis clearly confirmed the presence only of the orbital period (551.8 days) in the *U* band as well as the orbital (551.7 days) and pulsation (351.2 days) periods in *B* band (Fig. 4). The power spectrum in *V* band (Fig. 4) is more complex: although the orbital (547.2 bottom) and pulsation (350.6 bottom) periods were detected, the resulting power spectrum also contained other significant periods (334.1, 223.0 and 136.8 days). Though this may be only an artefact caused by the fact that amplitude of the light variations in the *V* band during quiescent stages of AG Dra is comparable to the observation errors in this band.

The interpretation of the time intervals between outbursts with a median of 365 days is more complicated. The emission spectral lines are created in the part of the symbiotic nebula, originating from the stellar wind of the red giant and ionized by radiation from the white dwarf. The stellar wind should be modulated by the giant pulsations. This modulation produces a Doppler shift of the spectral lines, that is manifested in radial velocities. Simultaneously also the number of emitted/absorbed particles, changes what is possible to detect in EW variability. Skopal et al. (2009) proposed another model, where the hydrogen lines are created in the wind of the hot component. In this case, the main role play is the mutual interactions of the wind on both components, but in this model, it is impossible to explain all observed effects.

Leibowitz & Formigini (2006, 2008, 2011, 2013) and Formigini & Leibowitz (2006, 2012) have found similar patterns in long-term light curves of six symbiotic stars, including AG Dra. The common feature of all these stars is the start of active periods at about 4650–7550 day intervals (12–20 years). This implies a common physical mechanism, for example, solar-like magnetic cycles, might be responsible for the activity of these symbiotic stars. However, there is no direct evidence of the presence of a reasonably strong magnetic field in the red giants in these systems. Complex morphology of the light curves may introduce artefacts in their period analysis. We suggest that a careful case by case analysis of the light curves together with spectroscopic data and when possible, observations in the wide wavelength range from X-rays to radio, would give first clues to understanding the physical mechanism of the outburst behaviour of

symbiotic stars. One should not pay too much attention to the possible artificial periods obtained from the analysis of the complicated light curves. The outburst phenomena are not necessarily strictly periodic as we have seen in the case of AG Dra. Let us be reminded that all the active periods of AG Dra have been different from each other (Figs. 1 and 3).

One of the promising explanations of at least some individual outbursts of AG Dra might be the combination nova model proposed for Z And by Sokoloski et al. (2006). In this model, when accretion rate onto the white dwarf exceeds some critical value, thermonuclear reactions are ignited and luminosity of the hot component increases significantly. One of the next task would be to study whether hot and/or cool outbursts of AG Dra will fit into such a picture. We will present a detailed analysis of the spectroscopic data of AG Dra in our forthcoming paper.

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We would like to devote this paper to the memory of our friend Michael Friedjung (1940–2011), long-term collaborator on AG Dra and other symbiotic stars. Michael suddenly passed away but we are sure that his wonderful spirit is now together with us.

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REFERENCES

- Andronov I. L., 1994, *Odessa Astronomical Publications* 7, part 1, 49
- Bastian U., 1998, *A&A*, 329, L61
- Belyakina T. S., 1965, *Izv. Krymskoj Astrofiz. Obs.*, Vol. 33, 226
- Belyakina T. S., 1969, *Izv. Krymskoj Astrofiz. Obs.*, Vol. 40, 39
- Breus V. V., 2003, *Odessa Astronomical Publications*, Vol. 16, 24
- Contini, M., Angeloni, R., 2011, *New Astronomy*, 16, 199
- Friedjung M., Hric L., Petrík K., Gális R., 1998, *A&A*, 335, 545
- Friedjung M., Gális R., Hric L., Petrík K., 2003, *A&A*, 400, 595
- Fekel F. C., Hinckle, K. H., Joyce, R. R., Skrutskie M.F., 2000, *AJ*, 120, 3255
- Formigini, L., Leibowitz, E. M., 2006, *MNRAS*, 372, 1325
- Formigini, L., Leibowitz, E. M., 2012, *MNRAS*, 422, 2648
- Gális R., Hric L., Friedjung M., Petrík K., 1999, *A&A*, 348, 533
- Garcia, M. R., 1986, *AJ*, 91, 1400
- Ghedini, S., 1982, *Software for photometric astronomy*, Richmond, Va., Willmann-Bell
- González-Riestra, R., Viotti, R., Iijima, T., Greiner, J., 1999, *A&A*, 347, 478

- Hric, L., Skopal, A., 1989, *Inf. Bull. on Var. Stars*, 3364, 1
- Hric, L., Skopal, A., Urban, Z., Petřík, K., Komžík, R., Chochol, D., Pribulla, T., Niarchos, P., Rovithis-Livaniou, H., Rovithis, P., Velič, Z., Okša, G., 1996, *Contributions of the Astronomical Observatory Skalnaté Pleso*, 26, 46
- Huang, C. C., Friedjung, M., Zhou, Z. X., 1994, *A&AS*, 106, 413
- Kaler, J. B., 1987, *AJ*, 94, 437
- Kenyon S.J., Fernandez-Castro T., 1987, *AJ*, 93, 938
- Korhonen H., 2013, private communication
- Leibowitz, E. M., Formigini, L., 2006, *MNRAS*, 366, 675
- Leibowitz, E. M., Formigini, L., 2008, *MNRAS*, 385, 445
- Leibowitz, E. M., Formigini, L., 2011, *MNRAS*, 414, 2406
- Leibowitz, E. M., Formigini, L., 2013, *AJ*, 146, 117L
- Leedjärv L., Burmeister M., Mikolajewski M., Puss A., Annuk K., Galan C., 2004, *A&A*, 415, 273
- Leedjärv L., Burmeister M., 2012, *Baltic Astronomy*, 21, 131
- Luthardt, L., 1983, *Mitteilungen über Veränderliche Sterne*, 9, 129
- Meinunger, L., 1979, *Inf. Bull. on Var. Stars*, 1611, 1
- Mikolajewska J., Kenyon S.J., Mikolajewski M., Garcia M.R., Polidan R.S., 1995, *AJ*, 109, 1289
- Mikolajewska, J., 2002, *MNRAS*, 335, L33
- Munari, U., Siviero, A., Ochner, P., Wallerstein, G., Castellani, F., Righetti, G., Cherini, G., Valisa, P., Cetrulo, G., 2009, *PASP* 121, 1070
- Press, W.H., Teukolsky, S.A., Vetterling, W.T., Flannery, B.P., 1992, *Numerical Recipes : The Art of Scientific Computing*, Second Edition, Cambridge University Press, New York
- Robinson L., 1969, *Peremennye Zvezdy*, 16, 507
- Schwarzenberg-Czerny, A., 1991, *MNRAS*, 253, 198
- Shore, S. N., Genovali, K., Wahlgren, G. M., 2010, *Baltic Astronomy*, 21, 139
- Shore, S. N., Wahlgren, G. M., Genovali, K., Bernaber, S., Koubský, P., Šlechta, M., Škoda, P., Skopal, A., Wolf, M., 2012, *A&A*, 510, 70
- Skopal, A., Chochol, D., 1994, *Informational Bulletin on Variable Stars*, 4080, 1
- Skopal, A., Hric, L., Chochol, D., Komžík, R., Urban, Z., Petřík, K., Niarchos, P., Rovithis-Livaniou, H., Rovithis, P., Oprescu, G., 1995, *Contributions of the Astronomical Observatory Skalnaté Pleso*, 25, 53
- Skopal, A., 1998, *Contributions of the Astronomical Observatory Skalnaté Pleso*, 28, 87
- Skopal, A., Vaňko M., Pribulla T., Wolf M., Semkov E., Jones A., 2002, *Contrib. Astron. Obs. Skalnaté Pleso*, 32, 62
- Skopal, A., Vaňko, M., Pribulla, T., Velič, Z., Semkov, E., Jones, A., 2004, *Contrib. Astron. Obs. Skal. Pleso*, 34, 45
- Skopal, A., Sekeráš, M., González-Riestra, R., Viotti, R.F., 2009, *A&A*, 507, 1531
- Skopal, A., Shugarov, S., Vaňko M., Dubovský, P., Peneva, S. P., Semkov, E., Wolf, M., 2012, *Astronomische Nachrichten*, Vol.333, 242
- Smith, V. V., Cunha, K., Jorissen, A., Boffin, H. M. J., 1996, *A&A*, 315, 179
- Sokoloski, J. L., Kenyon, S. J., Espey, B. R., 2006, *ApJ*, 636, 1002
- Splittgerber, E., 1974, *Mitteilungen über Veränderliche Sterne*, 6, 193
- Zamanov, R. K., Bode, M. F., Melo, C. H. F., Bachev, R., Gomboc, A., Porter, J., Pritchard, J., 2007, *MNRAS*, 380, 1053